R. Snowden.

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SYMPOSIUM ON HIGH ENERGY ACCELERATORS

(A.E.R.E., Harwell, 13/14th May, 1955)

SUMMARY OF PROCEEDINGS

by

T.G. Pickavance

A.E.R.E. Harwell.

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1. INTRODUCTION

The meeting, opened by Sir John Cockcroft, was called to consider high energy accelerator development in the United Kingdom for the next 5-10 years.

2. THEORETICAL BACKGROUND

In a survey of the fundamental physics underlying high energy accelerators, Peierls made the following points:

1. We should consider physics about eight years in advance, since four or five years will be needed to build a machine and it should have a reasonably long useful life. Therefore arguments about specific experiments should not be taken too seriously, but the flexibility and adaptibility of different machines are important considerations.

2. One should not ignore the possible occurrence of unforeseen but valuable results in apparetly well-understood fields. Studies at higher energies of effects involving electrons and radiation should not be ruled out.

3. In the continued absence of an adequate theory of nuclear forces on which to make quantitative experimental checks, experiments should be designed to give a clue to theoretical interpretation or to give a lead for further experiments. This would require all possible features of the experimental events to be investigated as closely as possible. For example, we would wish to know the nature and momenta of all the particles involved, and the cross sections of the processes as a function of energy.

4. As the bombarding energy is increased, for example in order to include heavy mesons and hyperons in the s tudy, the experimental difficulties are increased. Some of these difficulties are caused by the multiplicity and short lives of the particles produced, particularly when neutral particles are involved. Others have to do with the fact that high particles energies cannot be measured with the help of the range - energy relation, and cumbersome techniques such as magnetic analysis have to be used.

5. A premium is put upon intensity by (3) and (4), in a field where intensity is hard to get.

6. Intensity can be effectively increased by increasing the efficiency of particle detection, usually at a lower cost than that of making a similar increase of the beam current of an accelerator. This justifies a considerable expenditure of effort and ingenuity on experimental techniques.

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3. EXPERIMENTAL BACKGROUND

Moon stressed the importance of the slow increase of available energy in centre of mass space as the bombarding energy is increased. Thus the Bevatron produces only about 2 GeV in a p-p collison, and the new 25 GeV machines will yield only about 6 GeV. He also emphasised the necessity for increasingly refined experimental techniques in work on high energy processes, particularly when studying short-lived phenomena.

Intensities would have to be increased, with well-collimated external beams. There was some hope that more particles might ultimately be injected into conventional machines, but the repetition rates of these machines were low - a few pulses per minute. From this point of view development of the fixed field machines recently proposed would be of first-rate importance.

With intensities of the order of 10^{13} particles per cm^2 per pulse, the possibility of operating two accelerators back to back, so as to obtain a few proton-proton collisions with the centre of mass at rest in the laboratory frame, could be considered. This might be the only way of producing collisions involving > 10 GeV or so, at reasonable cost.

Moon strongly supported Peierls' view that expenditure and effort an experimental techniques should be high.

4. PROTON MACHINES IN THE U.S.A.

Pickavance reviewed the status of these machines.

They were:

Operating

Cosmotron	Brookhaven	C.G.	3 GeV $4 \cdot 10^{10}$/pulse 12 pulses/minute
Bevatron	Berkeley	C.G.	6.1 GeV 10^{10}/pulse 10 pulses/minute

Planned and approved

	Brookhaven	A.G.	25 GeV

Planned, not yet approved

MURA Group	F.F.A.G.	10-30 GeV
Princeton	C.G.	2-3 GeV

(High repetition rate, high pulse current)

Contemplated, but in a very early or uncertain stage

Argonne Laboratories	A.G., F.F.A.G.	10-30 GeV
Chicago	F.F.A.G. cyclotron	2 GeV
Oak Ridge	F.F.A.G. cyclotron	0.5-1 GeV

5. ELECTRON MACHINES IN THE U.S.A.

Ramsey reviewed the status of the following machines:

Operating

California Institute of Technology	C.G. electron synchrotron 600 MeV (to be increased to 1 GeV)
Stanford University	Linear electron accelerator 600 MeV (to be increased to 1 GeV)
Cornell University	A.G. electron synchrotron 600 MeV (to be increased to 1-1.5 GeV)

Planned

M.I.T. and Harvard University — A.G. electron synchrotron 5-6 GeV, 30 pulses/second

Contemplated

Stanford University — Linear electron accelerator > 10 GeV.

University of Pennsylvania and/or Princeton University — C.G. synchrotron, for protons or electrons. 2-3 GeV.

6. C.E.R.N. PROJECT

Adams described the C.E.R.N. 25 GeV project in a recorded talk. The following points were given particular emphasis:

1. Remanent field difficulties, making necessary very close control of the magnet iron in manufacture and in assembly.

2. Dimensional tolerances on the complete machine - e.g., the 1000 magnet blocks must be in a plan within 0.3 mm. R.M.S. and in a perfect circle within 0.6 mm. R.M.S., on a radius of 100 metres.

3. Transition energy, at which a change of R.F. phase has to be made. Near the transition energy extremely tight frequency control is needed.

4. Non-linear effects in the guiding field must be kept as small as possible.

5. Staff required. Adams gave the following figures for the size of his group on 31/12/55:

Senior Scientific	Junior Scientific	Senior Technical	Junior Technical	Total
26	19	10	67	122

7. PHYSICS OF PROTON SYNCHROTRONS

Walkinshaw contrasted conventional (constant gradient) proton synchrotrons with alternating gradient machines. He outlined the conditions for particle stability, emphasising the small size of the "stability diamond" in the A.G. machines, and showed that here only one revolution at injection could be expected. In contrast, protons in the Bevatron make about 150 turns at injection, with a corresponding increase of accelerated beam current for a given time of revolution.

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8. PHYSICS OF F.F.A.G. MACHINES

Mullett reviewed the new fixed field machines proposed by Symon and the MURA group under Kerst. Fixed fields may be used in such a way as to contain a large momentum range in a small range of radii (synchroton-type machine), or to produce constant angular velocity of relativistic particles, with a large range of radii (cyclotron-type machine). High intensity is possible, because there is now no problem of recycling large amounts of energy in the magnet. Further, with the cyclotron-type machine there arises the possibility, in principle, of continuous operation instead of pulsed operation.

Two methods of overcoming the defocusing inherent in the required field distributions are:

1. Reverse field ("Mark I"). Here the field gradient is the same in all magnet sectors, but the field direction (and therefore direction of bending) is reversed in alternate sectors. Such machines are necessarily of "synchrotron" type, and in practice would have a diameter about 5 times that of conventional C.G. or A.G. machines. This, with the consequent expense, would appear to preclude their use for very high energies (e.g. 25 GeV) in the near future.

2. Spiral ridge ("Mark V") machines. Bending is now unidirectional, and focusing is achieved by applying a series of spiral ridges to the pole pieces, making a small angle with the particle orbits and producing a "flutter" of field intensity on the median plane of about $\pm$ 10%. Such machines would be economical to construct, and the method could be applied to cyclotron-type accelerators.

The fields in these machines are extremely non-linear (especially in the spiral-ridge form) and very difficult to treat theoretically. The "stability diamond" in the synchrotron-type is much smaller than that in comparable A.G. machines, and in the cyclotron-type the particles have to traverse resonances if continuous operation is to be achieved.

In the synchroton-type machines, frequency modulation is required, and for a useful gain of intensity over planned A.G. machines the R.F. problem is formidable since very high powers are also required. The problem of phase-slip in large cyclotron-type machines (which have no phase stability if continuous operation is desired) is severe, and might have to be overcome by the use of frequency modulation. This solution would be at the expense of intensity.

Despite the obvious severe difficulties, these machines are so promising that considerable effort on design study is justified. This applies especially to the cyclotron-type machine.

9. VALUE OF A 2-3 GeV MACHINE FOR HIGH INTENSITY

Mandle made the case for a proton machine giving much higher than conventional synchrotron intensities at an energy between 2 and 3 GeV. He felt strongly that much of the work which could be done with a 10-15 GeV A.G. synchrotron would have been done with the Cosmotron and the Bevatron during the next 5 years, and that the remainder could be adequately covered by the 25 GeV machines at Brookhaven and C.E.R.N. which would be coming into operation at that time. The intensities of all these machines were quite low, and much greater intensities would be needed for the precise and refined experiments which must logically follow the initial surveys. These higher intensities would be valuable in any energy range, but at energies around 10 GeV or so the accelerator physicists would require a long time to study the difficult technical problems involved. Anderson was of the opinion that a high intensity 2 GeV cyclotron-type machine, using F.F.A.G. focusing, would be much easier from this point of view and might cost $ 7,000,000. There were difficulties, of course, but Anderson felt that a vigorous design study should show how to overcome them in 1-1½ years. Anderson mentioned the optimistic current of 100 μa, but it should certainly be possible to get 1 or 2 μa and this would give an enormous advantage over all existing machines, which give at most 10^{-3} μa at this energy.

Mandle then discussed the value of these intensities for detailed studies of pion-nucleon scattering, multiple pion production and K meson studies near threshold.

He said that there was a considerable measure of agreement in the U.S.A. that a high intensity machine in the 2 GeV region should have first priority in any future plans, and that several institutions there were becoming very interested in such projects. We should not miss the boat.

10. DESIGN STUDY OF A 12 GeV A.G. PROTON SYNCHROTRON

Pickavance outlined the results of a Harwell design-study on a possible machine which would use the 50 MeV proton linear accelerator as an injector, and would use similar magnet units to those designed by the C.E.R.N. group. The following are some of the parameters given in the talk:

Machine radius	56.8 m.	
Magnetic field	12 kilogauss	
Magnet steel weight	1600 tons	
Field at injection	288 gauss	
n-value	141	
Vacuum chamber aperture	8 cm. x 12 cm.	
Number of magnet units	70	
Number of long straight sections	14	3 m. long
Number of short straight sections	56	1.6 m. long
Stored energy in magnet	5.10^6 joules.	

Comparison with hypothetical C.G. machines showed that A.G. focusing would have to be used if a useful intensity of 12 GeV protons were wanted at reasonable cost. The estimated cost of the 12 GeV A.G. machine was £3,000,000.

Machines with repetition rates varying between 12 pulses/minute (as C.E.R.N.) and 48 pulses/minute had been considered, and it was concluded that the 48 p.p.m. machine was about as feasible as the C.E.R.N. machine. Tolerances on remanent fields would be easier than at C.E.R.N., if 50 MeV injection were used in both places. Tolerances on misalignments would be similar. There would be greater difficulty with timing systems.

If the injected current were exactly the same as that now obtained at Berkeley (which was realistic) and no ions were lost after phase trapping (much less realistic) than the output current of the 48 p.p.m. machine would be:

8.10^8 protons/pulse, or 6.10^8 protons/second.

If the injected current could be improved by a factor 10, which might be possible, we should then have, in an ideal machine, 6.10^9 protons/second.

The output expressed as a ratio with respect to other machines would be:

$$\frac{\text{12 GeV A.G.s}}{\text{6 GeV Bevatron}} = \frac{1}{10}$$

$$\frac{\text{12 GeV A.G.s}}{\text{25 GeV CERN.}} \doteqdot 3$$

Improvements in current at injection must be presumed to affect all these three machines equally.

The possibility of further increase of repetition rate, beyond 48 p.p.m., would be considered. There did not appear to be much hope of a great increase, however, since the cost of magnet power equipment would rise very greatly at the point where condensers would be needed for energy storage, and the cost, complexity and difficulty of R.F. equipment would rise steadily with the repetition rate.

Bearing in mind progress already made elsewhere and at Harwell, 4½ years should suffice for construction, starting from the date of approval.

11. DESIGN STUDY OF A 3-6 GeV ELECTRON SYNCHROTRON

Lawson gave the results of a study of a machine very similar to the 5-6 GeV A.G. electron synchrotron proposed by the M.I.T. - Harvard study group. Some of the main parameters given were:

Overall radius	100 ft.
n-value	100
Aperture	4" x $1\frac{1}{2}$"
Number of sectors	48
Weight per unit	7 tons
Injection energy	20 MeV electron linear accelerator
Field at injection	32 gauss
Injector current	640 m.a. ≡ 10" particles/pulse
Repetition rate	30 pulses per second
Number of R.F. Cavities	16 for 6 GeV.

The magnet misalignment tolerances for a 6 GeV machine would be similar to those of the C.E.R.N. machine, but the tolerance on remanent field variation at injection would be tighter than C.E.R.N. by about a factor 6. If the injection energy were increased to 60 MeV, which would be desirable, the remanent field tolerances would still be about twice as tight as C.E.R.N. A 3 GeV machine would be somewhat easier than the 6 GeV one in all these respects, but the time available for injection would be reduced from 0.6 μsec. to 0.3 μsec.

The cost was estimated to be about £1.8 million for 6 GeV, and £1.05 million for 3 GeV. Staff requirements were given as:

	Physicists and engineers	Technical	D.O. and Workshops	Total
6 GeV	22	23	12	57
3 GeV	19	22	8	49

$4\frac{1}{2}$ years would be required for completion of the 6 GeV machine, and the 3 GeV machine might be 6-9 months quicker.

12. REMARKS ON ELECTRON ACCELERATORS

Frisch made the following comments regarding the question electrons vs. protons:

1. If one requires an energy E in c. of m. space, electrons need a laboratory energy of $E + E^2/2$, whereas protons need $2E + E^2/2$. (Energies in units of $M_{nucleon}\ c^2$).

2. Electrons produce a well-collimated beam of γ-rays, only 1" dia. at 20'.

3. Protons produce more background, due to the broader beam and to exploding nuclei. Cross sections for protons are a factor 100-1000 greater than these for electrons, but more electrons can be accelerated in a feasible machine.

4. Interpretation is easier with electrons, since the process are better understood.

5. An A.G. electron accelerator has no transition energy, but is limited on maximum energy by radiation loss.

13. DISCUSSION

The discussion on the papers and during the separate discussion session is summarised briefly below.

Blackett, Bhabha and others felt that a 12 GeV machine would be of great value in extending studies on K-mesons, hyperons and the anti-nucleon problem. Devons, Roberts and others stressed the importance of developing electronic detection techniques in these studies, and Mandl and others mentioned the use of large-solid-angle magnets and similar devices to increase useful intensity. There was general agreement that precise and detailed experiments would be essential by the time any machine could be completed, so that there would be a premium on intensity. Peierls made the point that an increase of detector efficiency was usually cheaper than a corresponding increase in machine output, and all agreed that machine programmes should be backed up with strong resources on the measurement side. American experience, that the annual cost did not change after commissioning a large machine, was quoted in this connection.

Mandl's proposition for a 2-3 GeV high intensity programme was supported by Massey, Skinner, Cassels and others. Wilkinson produced arguments in favour of a machine of 6 GeV but with at least 100 times the intensity of the Bevatron. He suggested that no machine should be constructed solely for studies of K-mesons, since such studies were already well advanced; he advocated 6 GeV on the basis of the thresholds of various hyperon processes, and the high intensity to enable detailed investigations to be pursued in these as well as the K-meson phenomena, and asked whether it was cheaper to get the higher intensities than the higher energies. Pickavance and Mullett felt that, if such a machine were to be constructed at acceptable cost and according to present knowledge, and F.F.A.G. type of accelerator would be called for. Moon expressed the view that much progress could be made in injecting more protons into synchrotron-type machines, and Oliphant supported this.

Some of Frisch's suggestions about the virtues of electron machines were challenged by Devons and others, who cited the bremmstrahlung spectrum, energy loss by soft shower production and the much smaller γ-ray cross-sections as factors in favour of protons. However, the electron machine proposed by M.I.T. and Harvard would give much more current than comparable proton machines, and there was obviously room for both kinds of machines.

Oliphant made a plea for a pioneering programme, with which he identified a 12 GeV accelerator, and Sir John Cockcroft expressed his preference for this machine. Peierls mentioned the classic case of the Lamb shift as an example of a vital and important result coming from an apparently well-understood field, and others did not regard 12 GeV as pioneering in view of the C.E.R.N. and Brookhaven plans. Oliphant also stressed the importance of clean beams from accelerators; high intensity was of little value if accompanied by high background.

There was a long discussion on the relative importance of nuclear emulsion and electronics techniques. This was important, since if it could be shown that nuclear emulsion techniques would be reasonably adequate, or alternatively that electronics techniques would be impossibly difficult, then the multi-GeV moderate intensity position could be made satisfactory by sending plates to Berkeley, Brookhaven and, ultimately, C.E.R.N. However, there was a general feeling that all techniques would have to be used and that, even if electronics failed, good statistics in elementary processes would have to be sought by the large scale use of bubble-chamber and diffusion chamber techniques. All these techniques would require long machine-time, and consequently more machines.

Opinions differed as to the relative parts to be played, in the quest for higher intensities, by improved experimental techniques and improved beam currents on existing or known types of accelerators. There was no difference of opinion as to the desirability of an accelerator with an assured high intensity, even if it should prove relatively costly. Peierls felt that existing machines were adequate to deal with π-meson physics in the lower energy region where only single production occurred.

Summing up, Sir John Cockcroft felt that the majority favoured the 12 GeV A.G. proton synchrotron. The meeting could not constitutionally take decisions, but notes would be circulated, together with a request for opinions as to which course should be adopted. He thought the feeling of the meeting was that there should also be a long term programme to include design studies of F.F.A.G. machines.

Massey questioned whether the 12 GeV machine would be the right one to choose, particularly in view of the British share in C.E.R.N., and he was supported by Skinner. Lord Cherwell thought that the choice should probably be for the 12 GeV machine, but that time was needed to consider this in the light of the record of the meeting, a summary of which would be circulated.